IMPROVEMENT OF THE PRIMARY LOW-FREQUENCY ACCELEROMETER CALIBRATION SYSTEM AT INMETRO

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Outline of the presentation

- Introduction
- Description of the experiments
- New Calibration system
- Results and Discussions
- Conclusions
Introduction

- The Vibration Laboratory (Lavib) of INMETRO is continuously looking forward the improvement of its calibration systems and methods in order to fulfill the rising metrological demands in Brazil.

- Low-frequency vibration measurements are of interest in many different fields, as for instance: energy production, environmental assessment, transportation, etc.
Low Frequency primary calibration system

1st Setup - Fringe Counting Method

Frequency range: 0.4 Hz to 160 Hz

Exp. Unc. (k=2): 0.35 %
Calibration result

Mean of the results obtained for two mounting positions

Calibration result

Position m1 (0°)
Position m2 (180°)
Supplementary interlaboratory comparison AFRIMETS.AUV.V-S2

Sensitivity magnitude from 0.4 Hz to 50 Hz

Regional Supplementary Comparisons and CIPM key comparison CCAUV.V-K3

Link between 3 RMO Comparisons
Low-Frequency Key Comparison CCAUV.V-K3

Technical protocol

• Type: Primary calibration of accelerometers
• Reference standard: ISO 16063-11
• Measurand: Complex sensitivity (magnitude and phase shift)
• Artifacts: 2 servo-accelerometers
• Frequency range: from 0.1 Hz to 40 Hz (mandatory from 0.4 Hz)
• Pilot laboratory: NIM / China

• INMETRO measurements – April/2015, weeks 16 & 17.
Goal with the New Calibration System

- Represent SIM in the KC CCAUV.V-K3
- Calibration in compliance with ISO 16063-11
- Calibration method capable to measure Magnitude & Phase
  - SINE APPROXIMATION METHOD (Method 3)
- Tentative to reduce the lower frequency limit to 0.2 Hz
Experimental measurement setups tested

1. Fringe counting system
   - Homodyne Michelson interferometer with 2 retroreflectors
   - 1 Photodetector Thorlabs PDA36A
   - DAQ NI PCI-6115 + frequency counter
   - LabView software running the FC method

2. Comercial Laser Doppler Vibrometer system Polytec VDD-660
   - Software Vibsoft

3. Heterodyne interferometer with a flat moving mirror
   - Polytec Laser Head OFV 505 + customized Junction box VDD-Z011
   - DAQ NI PCI-6115
   - LabView software running the SAM method

4. Homodyne quadrature interferometer with 2 retroreflectors
   - DAQ NI PCI-6115
   - LabView software running the SAM method
**Comercial LDV**

**Polytec VDD-660 + software Vibsoft 4.1**

- **Computer**
  - Software VIBSOFT 4.1
  - DAQ PCI NI-6110

- **Junction Box VDD-Z011**

- **Optical Head OFV-505**

- **Signal Generator**
  - f<sub>1</sub>

- **Power Amplifier**

- **Shaker**

**Manual setting of vibration level per frequency**
Laser head OFV-505 + Lavib SAM software

Computer

SAM Software LAVIB

DAQ PCI NI-6115

Junction Box VDD-Z011

Optical Head OFV-505

Polytec heterodyne interferometric sub-system

accelerometer

control acceleration chain

Fully computer controlled calibration of accelerometer sensitivity
Polytec laser vibrometer

VDD-660 system
Modified junction box VDD-Z011
I & Q analog output signals

A/D conversion with DAQ NI 6115
• 12 bit resolution
• 4 channel simultaneous sampling
• 10 MS/s max. sampling rate

LabView software
Michelson interferometer with 2 retroreflectors and LAVIB FC software

Fully computer controlled calibration of accelerometer sensitivity
Homodyne quadrature interferometer + Lavib software

Computer

SAM Software
LAVIB

DAQ PCI
NI-6115

Homodyne quadrature Interferometer

accelerometer

I
Q
V_{out}
V_{control}

IEEE-488

Signal Generator

f_1

Power Amplifier

control acceleration chain

shaker

Fully computer controlled calibration of accelerometer sensitivity
Modified Michelson interferometer with two retroflectors

He-Ne Laser

Photodetector

Retroflector 1

Retroflector 2

Accelerometer

Shaker table

$u_1(t)$

Interference fringes

$s(t) = \hat{s} \cos(\omega t + \varphi_s)$

Fringes per vibration period:

$R_f = \frac{f_{\text{fot}}}{f_1}$

Displacement amplitude:

$\hat{s} = R_f \frac{\lambda}{8}$
Homodyne quadrature interferometer with two retroflectors

\[
s(t) = \hat{s} \cos(\omega_1 t)
\]
Method 3: Sine approximation  (ISO 16063-11)

Simultaneously sampling the quadrature signals and the transducer output signal, discrete time-series are obtained: \{u_1(t_i)\}, \{u_2(t_i)\} e \{u(t_i)\}

Discrete total modulation phase:

\[ \varphi_{\text{Mod}}(t_i) = \tan^{-1}\left( \frac{u_2(t_i)}{u_1(t_i)} \right) + n\pi \]

Phase unwrap:

A discrete displacement series \(s(t_i)\) can then be calculated from \(\varphi_{\text{Mod}}(t_i)\):

\[ s(t_{i+1}) - s(t_i) = \frac{\lambda}{4\pi} \left[ \varphi_{\text{Mod}}(t_{i+1}) - \varphi_{\text{Mod}}(t_i) \right] \]

Determination of the parameters of the modulated phase \(\varphi_M(t_i)\):

Multiple linear regression

\[ \varphi_{\text{Mod}}(t_i) = b_0 + b_1 \cos \omega t_i - b_2 \sin \omega t_i \]

Least squares solution

\[ b = (X^T X)^{-1} X^T Y \]

Amplitude of the modulated phase:

\[ \hat{\varphi}_M = \sqrt{b_1^2 + b_2^2} \]

Phase:

\[ \varphi_s = \tan^{-1}\left( \frac{b_2}{b_1} \right) \]

Displacement amplitude:

\[ \hat{S} = \frac{\lambda}{4\pi} \hat{\varphi}_M \]
Method 3: Sine approximation

The equation for the transducer output can be written in its discrete form:

\[ u(t_i) = \hat{u} \cos \varphi_u \cos \omega_i t_i - \hat{u} \sin \varphi_u \sin \omega_i t_i \]

Multiple linear regression

\[ u(t_i) = b_{u0} + b_{u1} \cos \omega_i t_i - b_{u2} \sin \omega_i t_i \]

Least squares solution:

\[ b = (X^T X)^{-1} X^T Y \]

Signal amplitude:

\[ \hat{u} = \sqrt{b_{u1}^2 + b_{u2}^2} \]

Phase:

\[ \varphi_u = \tan^{-1}\left(\frac{b_{u2}}{b_{u1}}\right) \]

Sensitivity:

Amplitude:

\[ \hat{S}_{ua} = \frac{\hat{u}}{\hat{a}} \]

Phase shift:

\[ \Delta \varphi = (\varphi_u - \varphi_a) \]

Acceleration amplitude:

\[ \hat{a} = \pi \lambda f^2 \hat{\varphi}_M \]

Phase:

\[ \varphi_a = \varphi_s + \pi \]
Quadrature distortion correction

Homodyne quadrature interferometer may not allow a perfect circle to be obtained when plotting $u_2 \times u_1$. This distortion can cause errors in the determination of the total interferometric phase $\varphi_{Mod}(t_i)$ by the arctangent demodulation $\arctan(u_2/u_1)$.

Errors:
- unequal gain of the two photo detection channels
- lack of quadrature (deviation from the $\pi/2$ nominal phase between the signals)
- different offsets

Effects:
- deformation of the circle into an ellipse
- offset from the (0,0) centre of the ellipse

Correction:
- LS ellipse fit to experimental data and correction of the errors effects
- Results in a circle centered on (0,0)

\[ \hat{u}_1 \neq \hat{u}_2 \]

\[ \hat{u}_{d1} = \hat{u}_1 + p \]

\[ \hat{u}_{d2} = \frac{1}{r} (\hat{u}_2 \cos \alpha - \hat{u}_1 \sin \alpha) + q \]
Homodyne quadrature interferometer
Quadrature calibration system

- Simultaneous A/D acquisition of I&Q signals and accel. output:
  - System Polytec VDD-660 – DAQ NI PCI-6110, sampling freq. up to 5 MS/s
  - System Lavib - DAQ NI PCI-6115, sampling freq. up to 10 MS/s.
- Typical sampling frequency used from 0.2 Hz a 160 Hz in our experiments is 2 MS/s.
- Management of extended memory is needed for the acquisition and processing of large size vectors.
  - PC configured with Intel i7 processor, 32 GB RAM, 2 TB HD, 240 GB SSD HD, video board with 2 GB memory. Operational system is Windows 7 Pro 64 bits and software platform LabVIEW 32 bits.
- I&Q signals – high frequency content
- Accelerometer – long periods of acquisition (integer number of periods to avoid windowing effects)
  - 10 times the vibration period
Lavib SAM software - Streaming to disk

- Software was developed to optimize the use of PC memory.
- Packages of data with fixed length are A/D converted and streamed to disc in a cyclic process.
- These packages are later recovered and appended in sequence to obtain data vectors with the resolution and length compatible with each vibration frequency.
- After applying the arctangent demodulation and phase unwrap algorithm data decimation is used to reduce vectors size.
Cyclic streaming data to disk

Package 1

Package 2

Package 3

Recovery and appending of N saved packages

Integer number of vibration periods \((10 \times T_1)\)
# Acquisition parameters

<table>
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<th>Frequency [Hz]</th>
<th>Period [s]</th>
<th># Samples</th>
<th>Sampling rate [Samples/s]</th>
<th># packages</th>
<th>Acquisition time [s]</th>
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</table>
Data processing (example for 1 Hz)

Interferometric signals

- A/D conversion
  - Rate = 2 MSa/s
  - # Samples = 250 kSa

- Save package to disk
  - (T = 0.125 s)

- Decimation (factor = 20)

- Save reduced data to disk
  - (T = 10 s)
  - Length = 20 MSa

- 2 Stacks of 80 packages
  - (T = 10 s)
  - Length = 20 MSa

Recovery of I&Q signals saved to disk

- (T = 0.125 s)
  - 2 MSa/s
  - 250 kSa

Ellipse fit Correction

\[
\tan^{-1}\left(\frac{u_{c2}}{u_{c1}}\right)
\]

Phase unwrap

Decimation (factor = 20)

Save reduced data to disk

- (T = 10 s)
  - 12.5 kSa

1 Stack of 80 reduced packages

- (T = 10 s)
  - Length = 1 MSa

Interferometric signals

- \( I(t) \)
- \( Q(t) \)

Displacement vector

- \( \hat{s}_{SAM} \)
- \( \hat{\varphi}_{SAM} \)

SAM

Repeat for \( N \) packages

Repeat for \( N \) packages

- 2 Stacks of 80 reduced packages
  - (T = 10 s)
  - Length = 1 MSa
Data processing (example for 1 Hz)

- Transducer output signal $u(t)$
- A/D conversion:
  - Rate = 2 MSa/s
  - $\#$ Samples = 250 kSa
- Recovery of I&Q signals saved to disk:
  - $T = 0.125$ s
  - 2 MSa/s
  - 250 kSa
- Decimation (factor = 20)
- Save reduced data to disk:
  - $T = 10$ s
  - 12.5 kSa
- Save package to disk:
  - $T = 0.125$ s
  - 2 Stacks of 80 packages
  - $T = 10$ s
  - Length = 20 MSa
- Repeat for $N$ packages

- Transducer output vector $u(t_i)$
- SAM
- $\tilde{u}_{SAM}$
- $\varphi_{uSAM}$
- 1 Stack of 80 reduced packages:
  - $T = 10$ s
  - Length = 1 MSa
- Repeat for $N$ packages
LAVIB calibration software (SAM)
Calibration results

Servo-accelerometer Allied Signal QA-3000 + 5 kΩ shunt resistor

A deviation can be observed above 5 Hz, when the acceleration level rises from 2 m/s² up to 3.5 m/s².

This increase in acceleration level is usually applied to improve the signal-to-noise ratio on the transducer output signal.
Probable cause

Fringe Counting Method (FC)

- Broadband measurement
- Noise and harmonic distortion components can generate extra fringes
- Increase in motion amplitude
- Decrease in sensitivity

Sine Approximation Method (SAM)

- Narrowband measurement
Amplitude linearity test  

freq. = 10 Hz

Measurement of sensitivity for different acceleration amplitudes

![Graph showing relative difference of sensitivity magnitude and phase shift against acceleration amplitude.](image)
Amplitude linearity test

freq. = 10 Hz

Measurement of sensitivity for different acceleration amplitudes
Phase response

Comparison of results from 3 measurement setups

SAM  ➡  Difference smaller than 0,01°
Key comparison CCAUV.V-K3

DoEs to the KCRV

$U = 0.25\%$ for magnitude
$U = 0.25^\circ$ for phase
Conclusions

- The new system presented allowed INMETRO to improve its measurement capability for vibration calibrations in low frequencies.

- SAM presents higher immunity to noise and THD than FC

- Primary calibrations of complex sensitivity (mag & phase) are already possible from 0.2 Hz to 160 Hz.

- Current CMC of INMETRO for magnitude - Exp. Unc. is 0.35%

- Key comparison CCAUV.V-K3 allowed us to check the equivalence between results obtained by several NMIs
  - Lower uncertainty was reported using the new system:
    - 0.25% for magnitude and 0.25° for phase
  - Calculated DoEs smaller than 0.15% for magnitude and 0.1° for phase
Thank you for your attention!

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